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EXPERIMENTAL STATUS OF $K \rightarrow \pi \nu \bar{\nu}$

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ABSTRACT

The experimental program for the study of the rare kaon decays, $K \rightarrow \pi \nu \bar{\nu}$, is summarized. A review of recent results is provided along with a discussion of prospects for the future of this program. The primary focus of the world-wide kaon program is the two golden modes: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. The first step in an ambitious program to precisely measure both branching ratios has been successfully completed with the observation of two $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events by E787. The E949 experiment is poised to reach an order of magnitude further in sensitivity and to observe ~ 10 Standard Model events, and the CKM experiment should observe ~ 100 SM events by the end of this decade. Limits on the neutral analog $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ have been set by KTeV and within the next couple of years will be pushed by E391a. Measurements of the branching ratio should be made within the next 10 years by KOPIO, with a goal of ~ 50 events, and at the JHF, with a goal of up to 1000 events.

1 Introduction

The primary focus in kaon physics today is the two golden modes: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. These modes are interesting as there is essentially no theoretical ambiguity in extracting fundamental CKM parameters from measurements of the branching ratios^{1, 2)}. The intrinsic theoretical uncertainty in $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ is $\sim 7\%$ and is even smaller in $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$, only $\sim 2\%$; in both cases the hadronic matrix element can be extracted from the $K^+ \rightarrow \pi^0 e^+ \nu_e$ (K_{e3}) decay rate.

The unitarity of the CKM matrix can be expressed as

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = \lambda_u + \lambda_c + \lambda_t = 0$$

with the three vectors $\lambda_i \equiv V_{is}^* V_{id}$ converging to form a very elongated triangle in the complex plane. The length of first vector $\lambda_u = V_{us}^* V_{ud}$ is precisely determined from K_{e3} decay. The length of the third side $\lambda_t = V_{ts}^* V_{td}$ is measured by $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and the height of the triangle, $Im \lambda_t$, can be measured by $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. Branching ratio measurements of the two $K \rightarrow \pi \nu \bar{\nu}$ modes, along with the well known K_{e3} , will completely determine the unitarity triangle.

Comparison of CKM parameters as measured from the golden $K \rightarrow \pi \nu \bar{\nu}$, $B_d^0 \rightarrow \psi K_S^0$ and $\Delta M_{B_d}/\Delta M_{B_s}$ modes, provide the best opportunity to over-constrain the unitary triangle and to search for new physics. In particular, comparisons of

- $|V_{td}|$ from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and from the ratio of the mixing frequencies of B_d and B_s mesons $\Delta M_{B_d}/\Delta M_{B_s}$ ²⁾,
- β from $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})/B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and from the time dependent asymmetry in the decay $B_d^0 \rightarrow \psi K_S^0$ ^{3, 4)}

offer outstanding opportunities to explore the Standard Model (SM) picture of CP -violation.

The SM prediction for the $K \rightarrow \pi \nu \bar{\nu}$ branching ratios are $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.72 \pm 0.21) \times 10^{-10}$ and $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (0.26 \pm 0.12) \times 10^{-10}$ ¹⁾. In addition, an upper limit on $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ can be derived with small uncertainty from the current limit on B_s mixing; this limit is $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.32 \times 10^{-10}$ ⁵⁾.

2 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

The Alternating Gradient Synchrotron (AGS) as a high-energy physics (HEP) research facility has had a broad and rich program in kaon physics, culminating in the observation of two $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events by E787. With the recent successful commissioning of the Relativistic Heavy Ion Collider (RHIC), the primary role of the AGS has shifted to become an injector of heavy ions for RHIC. Nevertheless, the AGS remains the highest intensity proton synchrotron in the world and is designed to be available for ~ 20 hours/day when not filling RHIC, and as such retains an important role in the US HEP program. DOE and BNL have approved and agreed to fund one new HEP experiment to run at the AGS between RHIC fills: the E949 experiment seeks to make a precise measurement of the branching ratio $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$. While DOE approved E949 to run for 60 weeks, the FY03 budget of the President of the United States does not include running for E949. At this point the E949 experiment will be terminated after only 12 weeks of running, unless the US Congress restores funding. The fate of the E949 experiment will not be known until Congress initiates and then completes the appropriations process between June and October of 2002.

The completion of the Main Injector (MI) at FNAL allows for the simultaneous operation of a fixed target program along with the Tevatron collider. The next step in the pursuit of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ will be the CKM experiment, which plans to use a modest fraction of the MI protons (5×10^{12}), extracted over a 1-second spill with minimal bunching of the proton beam, and will push the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ sensitivity to the current limits of theoretical precision.

2.1 E787

The first $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal was observed in the 1995 data sample of the E787 experiment ⁶⁾. No new events were seen in the data sample from 1996–97 ⁷⁾, and with a background of 0.08 ± 0.02 events and a signal of one event a branching ratio of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$ was measured. That event was in fact in a very clean region of the predefined $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal region with a SM-signal to background ratio of 35. An analysis of the final E787 data sample from the 1998–99 run has recently been reported ⁸⁾. With a measured background of $0.066^{+0.044}_{-0.025}$, one new event was observed. The final plot of range vs. energy from the combined E787 1995–99 data sample for events passing all

other cuts is shown in Figure 1. The branching ratio, as determined from these

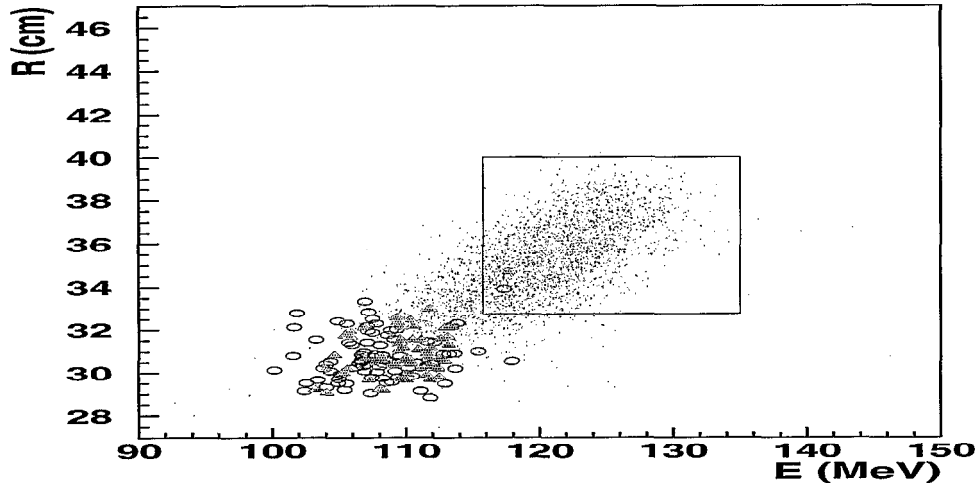


Figure 1: Final E787 plot of range vs. energy for events passing all other cuts. The circles are for 1998 data and the triangles are for 1995-97 data. Two clean $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events are seen in the box. The remaining events are $K^+ \rightarrow \pi^+ \pi^0$ background. A $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Monte Carlo sample (dots) is overlaid on the data.

two events, is

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}. \quad (1)$$

This branching ratio is a factor of two higher than expected in the SM and is higher than allowed by the current limit on B_s mixing. Of course, the uncertainty on the BR measurement is large due to limited statistics and new data from the E949 experiment are eagerly awaited.

The new event found in the 1998 data sample is in a relatively clean region of the accepted signal region: the SM signal to background ratio for this event is 3.6. An event display for this event, as well as the previous event, is shown in Figure 2.

Limits on $|V_{td}|$ and λ_t can be obtained (these are $1-\sigma$ limits except for $Im\lambda_t$ which is 90% CL),

$$\begin{aligned} 0.007 < |V_{td}| &< 0.030, \\ 2.9 \times 10^{-4} < |\lambda_t| &< 1.2 \times 10^{-3}, \end{aligned} \quad (2)$$

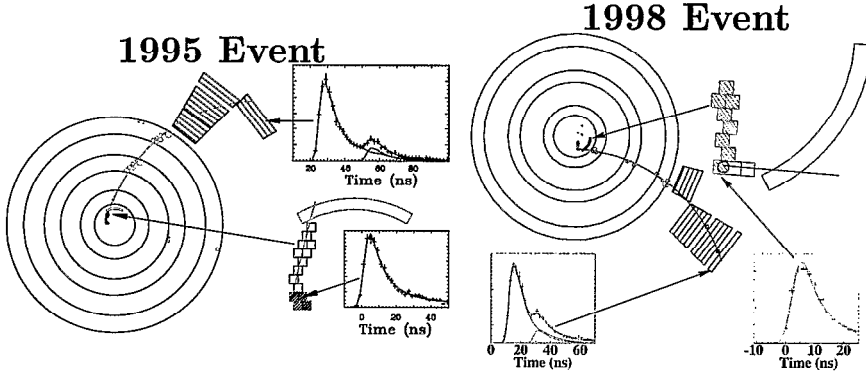


Figure 2: Graphical displays of the two $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events, discovered in the E787 data samples from 1995 and 1998. The display is an end view of the detector, with expanded views of the target region, and with views of the digitized pulses in the fiber where the kaon stopped and of the $\pi^+ \rightarrow \mu^+$ decay signal in the scintillator where the pion stopped.

$$-0.88 \times 10^{-3} < \text{Re} \lambda_t < 1.2 \times 10^{-3},$$

$$\text{Im} \lambda_t < 1.1 \times 10^{-3}.$$

Even with the large statistical error, this new measurement provides a non-trivial contribution to global fits of the CKM parameters ⁵⁾. The constraints on λ_t from this result are shown in Figure 3. The constraints from the other golden B modes, $\Delta M_{B_d}/\Delta M_{B_s}$ and $B_d^0 \rightarrow \psi K_S^0$ are shown on the same plot. One can immediately see that $|\lambda_t|$ is tightly constrained to a narrow crescent by $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $\Delta M_{B_d}/\Delta M_{B_s}$.

New data from the successor to E787, E949, will make a significant contribution to our knowledge of the CKM parameters.

In addition, E787 has searched for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the pion kinematic region below the $K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi 2}$) peak ⁹⁾. This region contains more of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ phase space, but is complicated by a significant background from $K^+ \rightarrow \pi^+ \pi^0$ decays with the π^+ scattering in the scintillating fiber target and shifting its kinematics into the search region. The data from the 1996 run of E787 has been analyzed ($\sim 20\%$ of the entire E787 data sample). One event

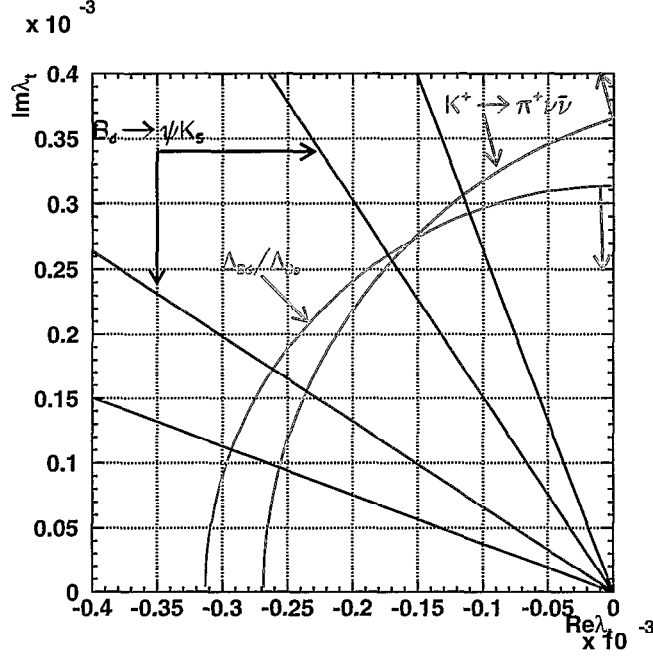


Figure 3: Constraints on λ_t from the golden modes. The experimental measurements for $B_d^0 \rightarrow \psi K_S^0$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ are 90% CL limits and for $\Delta M_{B_d}/\Delta M_{B_s}$ is a 95% CL limit. The theoretical uncertainties in all of these modes are small. A measurement of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ will determine $Im \lambda_t$. (I have used $\Delta M_{B_s} < 14.6 ps^{-1}$, $0.56 < B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 3.89$ and $\sin(2\beta) = 0.79 \pm 0.13$.)

was observed in the search region, consistent with the background estimate of 0.73 ± 0.18 . This implies an upper limit on $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 4.2 \times 10^{-9}$ (90% C.L.), and is consistent with the 2 events observed above the $K_{\pi 2}$ peak and the SM spectrum. Some additional reduction of the background levels in the remaining E787 data may be possible, but the major focus will shift to the new E949 experiment, which has significantly enhanced photon veto capabilities that will further suppress this background. In addition, the next experiment after E949, CKM at FNAL, will be essentially free of this background since there is no stopping target.

2.2 E949

E949 is an upgraded version of the E787 experiment, planning to capitalize on the full AGS beam to collect $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data at 14 times the rate of the E787 run in 1995. The new detector has substantially upgraded photon veto capabilities, enhanced tracking, triggering, monitoring, and DAQ capability, and will run at a higher AGS duty factor and a lower kaon momentum (with an increased fraction of stopped kaons). It has been designed to reach a sensitivity of at least 5 times beyond E787 and observe 5–10 SM events. The background level for E949 measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ above the $K_{\pi 2}$ peak is reliably projected from E787 data to be $\sim 10\%$ of the Standard Model signal.

E949 should see up to 10 SM events (or 20 events at the branching ratio measured by E787) within the next couple of years. This is an exciting opportunity to make a significant contribution to quark mixing and CP -violation that should be fully exploited. A history of the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is shown in Figure 4.

2.3 CKM

The next step towards a precision measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ will be the CKM experiment at FNAL. CKM has been given scientific (Stage-1) approval by FNAL and could be running by 2007. CKM plans to use a novel technique for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: a decay in flight experiment, with redundant kinematic constraints from a conventional momentum spectrometer and a novel velocity spectrometer based on RICH counters. CKM expects to observe 100 SM signal events in a two year run, using the Main Injector simultaneously with the Tevatron. The background is expected to be $\sim 10\%$ of the SM signal, predominantly from $K^+ \rightarrow \pi^+ \pi^0$. A vacuum of 10^{-6} Torr is required to minimize backgrounds from kaon interactions in the decay volume. CKM will require less than 20% of the flux from the Main Injector, but will require a slow extracted spill of ~ 1 second duration. CKM will run with a 50 MHz 22 MeV/c beam with RF separators and about 70% K^+ purity. Figure 4 shows a projected measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ from CKM, assuming the current central value of the branching ratio.

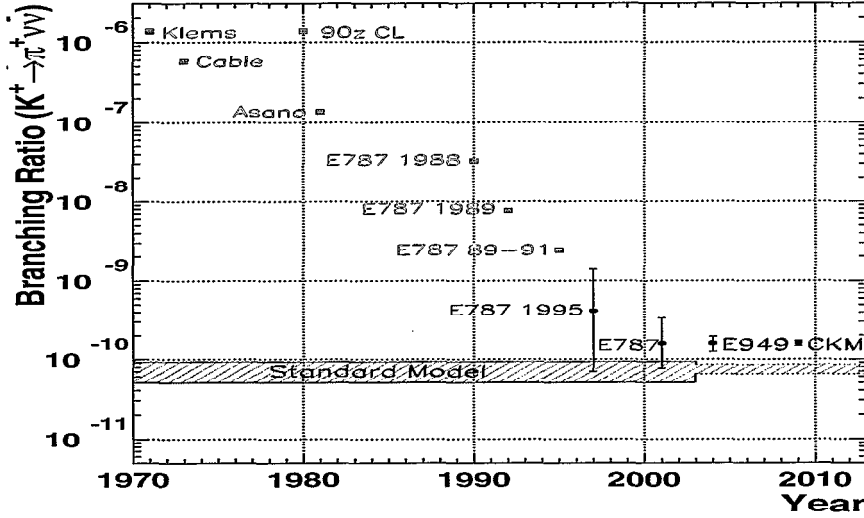


Figure 4: History of the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The squares represent 90% CL limits, the dark circles are the E787 observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, and the projections of the current central value of the branching ratio to the proposed E949 and CKM sensitivities. The prediction from the SM is expected to narrow considerably once $B_s^0 - \bar{B}_s^0$ mixing has been observed.

3 $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

The decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ is even cleaner theoretically and is CP -violating. However, it is even more challenging experimentally as all of the particles involved are neutral.

Presently, the best limit on $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ is derived in a model-independent way ¹⁰⁾ from the E787 measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:

$$\begin{aligned} B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) &< 4.4 \times B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \\ &< 1.7 \times 10^{-9} \text{ (90\% CL)}. \end{aligned} \quad (3)$$

Of course, it is desirable to observe this mode directly in order to extract a second constraint on the CKM matrix parameters. The current best direct limit is derived from a KTeV search for high transverse momentum π^0 's decaying

via $\pi^0 \rightarrow e^+e^-\gamma$. From the full 1997 data set, KTeV observed no events with an expected background of $0.12^{+0.05}_{-0.04}$ and set a 90%-CL limit ¹¹⁾ of

$$B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}. \quad (4)$$

Due to the small $\pi^0 \rightarrow e^+e^-\gamma$ branching ratio all future experiments plan to use the more copious $\pi^0 \rightarrow \gamma\gamma$ mode. KTeV also made a search in this mode in a special one day test, with a highly collimated ‘pencil’ beam and observed one background event, most likely from a neutron interaction, and set a 90%-CL limit ¹²⁾ of $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-6}$.

3.1 E391

The next generation of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ experiments will start with E391a at the High Energy Accelerator Research Organization (KEK) which hopes to reach a sensitivity of 3×10^{-10} . This experiment will use a technique similar to KTeV, with a pencil beam, high quality calorimetry and very efficient photon vetos. This is the first experiment dedicated to searching for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and aims to close the window for non-SM contributions to the decay. It will also serve as a test bed for the experimental techniques necessary to observe $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ in future experiments. Beam tests were started in 2001 and the first data-taking run is scheduled for 2003. This experiment plans to eventually move to the Japanese Hadron Facility (JHF) in ~ 2007 , and attempt to push to a sensitivity of $\mathcal{O}(1000)$ events.

3.2 KOPIO

The National Science Board of the National Science Foundation (NSF) has approved the construction of the two new large experiments at the BNL AGS: KOPIO and MECO, as components of the Rare Symmetry Violation Proposal (RSVP). RSVP is planned to be one of the next Major Research Equipment construction projects at the NSF.

The KOPIO experiment is designed to discover the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay and measure its branching ratio to $\sim 20\%$. KOPIO will make use of a time-of-flight technique to measure the momentum of the K_L and will operate at a large targeting angle to improve the p_K resolution and soften the neutron spectrum to reduce π^0 hadroproduction. All possible aspects of the decay will be measured: the photon directions will be measured in a pre-radiator, the times and

energy will be precisely measured in a Shashlyk calorimeter, the time of the kaon's creation is determined by the proton bunch width from the AGS (~ 250 psec). KOPIO will have a substantial photon veto system and make the same sort of background measurements as E787, directly from the data, with two independent tools for attacking the major background, $K_L^0 \rightarrow \pi^0 \pi^0$, through both kinematics and photon veto. KOPIO expects to observe 50 SM events, with a background of 50%. This will allow a determination of $Im\lambda_t$ to 10%. KOPIO is expected to start data collection in ~ 2006 .

4 Conclusion

The next decade will be an exciting time for improved understanding of CP -violation and quark mixing. It is quite likely that precise measurements of all four golden modes will be made: $B_d^0 \rightarrow \psi K_S^0$ at the B-factories; $\Delta M_{B_d}/\Delta M_{B_s}$, most likely at the Tevatron; and $K \rightarrow \pi \nu \bar{\nu}$ at BNL, KEK and FNAL. These measurements will allow a precise determination of CKM parameters and provide a critical test of the SM picture of CP -violation.

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